Unveiling the Formation of Massive Galaxies

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One of the primary goals of modern astronomy is understanding the formation history of galaxies. This problem can be subdivided into separate sub-questions, perhaps the most straightforward is understanding the formation of the most massive galaxies. There are well defined predictions for how massive galaxies should form [1,2] and massive galaxies are the easiest to study since they are usually the brightest at any given epoch. Massive galaxies in the nearby universe contain most of the stars [3] and are generally composed of old stellar populations [4]. However, it is difficult if not impossible to determine, within a few billion years, the ages of these galaxies using modern methods for dating stellar populations [4]. The solution to understanding the formation of massive galaxies is to study them in the early universe when they are forming at high redshift.

There are two questions concerning the formation of massive galaxies that astronomers are beginning to answer. These are understanding when and how these systems formed. Historically, most attention has been placed on determining when massive galaxies formed by identifying and measuring properties of galaxies at high redshift. The first ultraviolet selected samples of high redshift (at $z \sim 3$; about 11 billion years ago) galaxies demonstrated that these systems have number densities and clustering properties similar to nearby massive galaxies [5,6]. However, follow up determinations of the stellar masses of these galaxies, or the amount of mass in

a stellar form, showed that these galaxies have lower stellar masses, similar to the mass of the bulge of our own Milky Way galaxy [7]. Very few to none of these massive systems have stellar masses within a factor of ten of the most massive galaxies in the modern universe [7,8].

The total integrated stellar mass density at these redshifts is also roughly a factor of ten lower than the stellar mass density today [9]. It appears from these observations, and the fact that the star formation rate within galaxies is high up until redshifts $z \sim 1$ [10], that some massive galaxies did not form all their mass early. This is consistent with the Cold Dark Matter model for structure formation that predicts the most massive objects form gradually through accretion and merging [1]. Another possibility is that there are galaxies at redshifts $z \sim 3$ that are not identified in ultraviolet selected redshift surveys because they are made up of old stars or contain large amounts of dust. Both situations create galaxies with red spectral energy distributions which would be missed in traditional ultraviolet selected surveys [11].

It has been argued that populations of these red, possibly old and massive, galaxies have been found at $z \sim 1.5-3$ [11,12]. These systems are characterized by rest-frame optical colors similar to colors of nearby normal galaxies, and their clustering and stellar mass properties suggest that they are massive galaxies [13]. The integrated stellar mass density of these galaxies is roughly similar to the stellar mass density of the star bursting population at similar redshifts [11]. Determining how common these massive, possibly evolved, galaxies are will require deeper and wider near infrared imaging and spectroscopic surveys that are just now feasible.

Massive galaxies may also not be easily visible or identifiable in optical or near infrared surveys, because of high amounts of light extinction by dust. In the last decade, a significant population of bright sub-mm galaxies were found at redshifts $z > 2$ that are potentially precursors of contemporary massive galaxies [14]. These galaxies were discovered in deep sub-millimeter surveys that sample rest-frame far infrared radiation which originates from dust grains heated by photons from massive young stars. The dust in these galaxies absorbs energetic photons, and

it is not clear how much light from stars in these galaxies should be seen. However, the internal kinematics of these systems, based on the velocity width of the CO emission line, suggests that they are massive galaxies [15]. It is not yet known if these systems represent a phase of evolution that relates to galaxies chosen in ultraviolet and near infrared selected samples.

In addition to understanding when massive galaxies formed, astronomers are also investigating how this formation occurred. Assuming that we are not missing a large population of massive galaxies at high redshift, the higher number density of these systems at lower redshifts suggests that massive galaxies must have formed gradually through time. How does this occur? There are several possibilities, including: major mergers between galaxies of similar mass to build larger galaxies, minor mergers of smaller satellites, and the accretion of intergalactic gas which is converted to stars. Understanding which of these modes is responsible for forming massive galaxies is a fundamental problem that is just now being addressed.

Perhaps the most popular explanation is that the most massive galaxies formed through multiple major merger events. Major galaxy mergers are in fact a prediction of the Cold Dark Matter cosmology, and are found to occur in simulations of galaxy formation [1]. Understanding and tracing the extent of major mergers in the early universe is however difficult. Recently it has been shown that by using high resolution Hubble Space Telescope imaging, it is possible to determine the formation modes of galaxies. Specifically, we can identify systems undergoing major mergers by their peculiar and distorted structures. Within the Hubble Deep Field North the merger rate and history have been traced in detail as a function of galaxy luminosity and stellar mass [16]. Galaxies undergoing the most merging at high redshift, $z > 2$, are the most luminous and massive galaxies. By tracing the merger history for the most massive galaxies it appears that very few mergers occur in massive galaxies at lower redshifts [16]. This is consistent with finding massive evolved galaxies at modest redshifts [12] and is in direct conflict with the predictions of Cold Dark Matter models. Based on these observations, it appears that

massive galaxies do not form rapidly early in the universe, as in the traditional early monolithic collapse picture, but nor are they forming gradually throughout time as in Cold Dark Matter simulations.

It is however still not clear how the merging ultraviolet bright systems at $z \sim 2.5$ relate to the sub-millimeter and near infrared selected galaxies found at similar redshifts. It is likely that these represent various phases of galaxy evolution whose time-scales are still unknown. It is also likely that the environment of galaxies is a significant factor in their evolution [13] such that those in denser areas are forming earlier than galaxies in lower density environments. Little is understood of this effect at high redshift, but future deep infrared surveys should address this problem in the coming years.

References and Notes

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